Reverse Engineering Odontomachus

Undergraduate Honors Thesis

Presented in Partial Fulfillment of the Requirements

for Graduation with Distinction

at The Ohio State University

By

Angelica Kuei-Jen Liu

Department of Mechanical Engineering

The Ohio State University

2010

Defense Committee:	Approved by
Professor Blaine Winfred Lilly (Advisor)	______________________________
Professor John Wenzel	______________________________

ABSTRACT

The trap-jaw ant genus *Odontomachus* possesses the fastest mechanical movement known in nature. These ants are capable of closing their jaws at speeds of over 140 mph. This project, which I will continue for my M.S. in Mechanical Engineering, investigates the structural design of the trap-jaw mechanism from an engineering perspective. To this point, I have primarily focused on the shape of the head cuticle. Entomologists have traditionally treated the head structure as a rigid body, assuming that the potential energy required to close the jaws at such high velocity is stored primarily in the muscles and apodeme. In this project, we include the thin head shell itself in the functional model of the trap jaw mechanism, to determine if *Odontomachus* could have evolved a distinct head shape that stores potential energy in the deformed shell as well. Three–dimensional computer–aided CAD models of the *Odontomachus* head structure were developed, with which we developed finite element analyses to determine cuticle deflection and stress concentrations for the *Odontomachus* head. The same procedures were carried out for three additional head shape iterations. One iteration was based on the ant genus *Atta*, which has a very different head shape that is optimized for high force generation, rather than high closing speed. It was determined that the *Odontomachus* head structure has evolved to minimize both stress and deflection, which disproves our hypothesis. Gaining a better understanding of this mechanism will

aid entomologists in their study of these ants and may well lead to future engineering innovations in the area of very small scale robotics.

DEDICATION

This document is dedicated to my family.

ACKNOWLEDGMENTS

I would like to thank my advisors Professors Blaine Lilly and John Wenzel for their help, guidance and insight throughout this project. I would also like to thank entomologists Professor Bert Hölldobler at Arizona State University, Professor Wulfila Gronenberg at the University of Arizona, Professor Andrew Suarez at the University of Illinois, and Professor Joseph Spagna at William Paterson University for working with us and teaching engineers about the fascinating world of ants. Finally, I would like to thank Professors Jim Arnold, Rebecca Dupaix, and Lisa Abrams for all their help with the large amount of computer modeling and simulations involved in this project. Without the help of these individuals, this project would not have been possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Introduction and Literature Review

Biomimetics is a relatively new and rapidly expanding area of science; it is innovation inspired by nature [1]. Scientists use natural designs to solve problems in other disciplines such as engineering, medicine, and material science. One of the earliest and most commonly cited examples of biomimicry is the invention of velcro. An engineer thought of the design after looking at how burrs stuck to his clothing and his dog's fur after a long hike [1]. More recent research includes examination of the material properties of spider silk, which is five times stronger than steel, and investigation of how termites maintain almost constant temperature and humidity in their homes in Sub-Saharan Africa as a means of improving building designs.

This research project will focus on reverse engineering the mandible mechanism of the ant genus *Odontomachus* (Figure1), (Figure 2). *Odontomachus* is one of several trap-jaw ant genera [2] [3]. These ants possess the fastest mechanical movement known in nature; they are capable of closing their jaws at speeds of over 140 mph, with forces exceeding 300 times their body weight [4]. It is believed that the ants originally developed this mechanism solely for predation, but they now also use it for propulsion [4]. Ants of the *Odontomachus* genus can perform two types of jumps: the “bouncer defense” jump and the “escape jump”. In the bouncer defense jump, when confronted with a large intruder or intruding object, the ants will strike it while simultaneously propelling themselves laterally away from the threat (Figure 3) [4]. In the escape jump, the ants launch themselves vertically to avoid an intruder or predator (Figure 4) [4]. Ants orient their heads perpendicular to the surface of the ground, and trigger their jaws to snap shut, propelling themselves into the air [4]. Dr. Andrew Suarez of the University of Illinois Urbana-Champaign and his colleagues have analyzed the ballistics of these jumps using high-speed videography [4].

Entomologists have also investigated the anatomy of the ant head and mandible in general. There are two different types of muscles that ants use to open and close their jaws: slow muscle fibers (long sarcomeres) and fast muscles fibers (short sarcomeres) [5]. The muscle fibers are attached either directly or via filaments to the interior of the head and the apodeme (a tendon-like structure that attaches to the mandibles) [5]. Most ants possess both types of muscles in varying ratios depending on the mandible usage [5] [6]. The more fast muscle fibers an ant has, the faster the jaws can close, and likewise, the more slow muscle fibers an ant has, the slower the jaws can close. Fast muscle fibers generate much less force and are positioned along the length of the head, whereas slow muscle fibers are capable of generating very large forces (i.e. leaf cutter ants) and are positioned more laterally within the head[5]. *Odontomachus* ants are unique in that they possess mostly slow muscle fibers, yet because of the design of their jaws, they are capable of generating both large forces and high velocity [6]. The trap-jaw design works essentially like a catapult: the jaws are locked into their fully open position, and then the closer muscles are contracted. This stored potential energy is rapidly released when trigger hairs are stimulated, initiating an extremely fast strike [6]. Researchers have measured strikes that take less than 0.5 ms, and observed that the mandibles actually decelerate before hitting each other, though it is unknown how the deceleration is controlled [7]. Additional research has investigated the electrical impulses required to activate the trigger neurons [8] [9]. When *Odontomachus* ants do not employ the trap-jaw reflex, their jaws are among the slowest moving mandibles in ants because they have only slow closer muscle fibers [6] [10].

Some engineering analysis has been done with the trap-jaw mechanism, including investigation of the effects of scaling on the forces, velocity and acceleration generated [11]. A Masters student at the University of Illinois Urbana-Champaign began a two-dimensional analysis of the kinematics of the strike, but was unable to complete his research [12]. He also constructed a physical model of a basic design based on his analysis (Figure 5), although in this case, the locking mechanism was based on *Daceton armigerum*, a different species of trap-jaw ant [13]. *Daceton armigerum* do not use the notch and socket method of *Odontomachus*, but rather use a labrum which is lodged between the two mandibles and quickly removed when triggered [13] [14].

1.2 Project Objective and Overview

This project is the first of several possible research projects involving reverse engineering the *Odontomachus* trap-jaw mechanism. The main goal of the project was to explore how the mechanism works and determine where the focus should be placed for future research.

An extensive literature review was initially conducted to determine what relevant research could be found that pertained to the mechanics of the mechanism. This included information about the speeds and velocities of the jaws, general cuticle properties, and functional analyses of the mechanism. A full, kinematically correct model of the entire ant body was then produced. The model was created to gain a better understanding of the scale of the individual components of the ant as well as how various body parts moved in relation to one another.

Focus then shifted to examining the head structure. A detailed three–dimensional CAD model of the *Odontomachus* cuticle which makes up the head was created using CT scans provided by Dr. Andrew Suarez of the University of Illinois, Champagne. A simplified model was also created. Based on these models, a hypothesis was developed; it was thought that the shape of the head was actually optimized for use in the trap-jaw mechanism. That is, the head was shaped in such as way as to allow it to store some of the potential energy required for the mechanism to work. In order to test this hypothesis, several computer-aided design (CAD) iterations of the head were created, and finite element analyses (FEAs) were conducted to determine the deflection of each.

This project is part of a larger Master's thesis, which will continue next year. Ultimately, a three–dimensional working model will be constructed which will simulate the jaw–closing mechanism of the *Odontomachus* ant. The design will help biologists better understand the jaw mechanism and may also be used in small-scale robotics applications requiring both high force and high velocities.

CHAPTER 2: MODELING

2.1 Full Ant Model

The early stages of the project began with creating a full model of the ant species *Odontomachus bauri* using the images below. This was done to gain a better understanding of the proportions and overall kinematics of the ant. Though we knew that we would be exploring the trap-jaw mechanism of the *Odontomachus* ants, it was also important to understand how the overall system functioned kinematically.

Figure 1: Side and top view of an *Odontomachus bauri* specimen [16]

Each individually moving body part of the ant was created to scale, and the components were assembled to allow the proper degrees of freedom for each joint. The fully assembled model can be seen below in Figure 2. It was made up of 24 separate parts.

Figure 2: Full ant computer model

Based on this model, we began to also consider the proportions of the joints in relation to the full body. Specifically, the neck joint was of particular interest; there is a great deal of force transmitted to this joint when the trap-jaw mechanism is actuated in the jumping behavior, however there is no internal structural support. The connection is essentially made up of soft cuticle. The properties of this structure will be explored in future research.

2.2 Complex *Odontomachus* Model

The next step was to look more closely at the head and mandible structures. We started by focusing on the head structure. Our initial idea was to model the entire head cuticle, and carry out an FEA (Finite Element Analysis) on the structure to determine the stresses and deflections involved when the trap-jaw mechanism is carried out. We planned on applying all the forces involved in the entire process (when the jaws were locked in to place, loaded, released, and struck a hard surface).

Dr. Andrew Suarez of the University of Illinois, Champaign provided micro computed tomography (CT) scans to aid in modeling as shown in Figure 3.

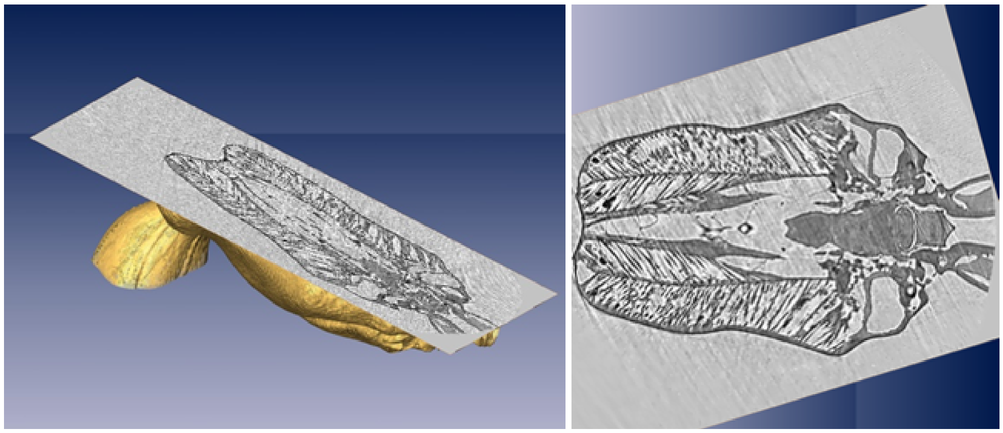

Figure 3: Micro CT scans of *Odontomachus bauri* head

We knew roughly how far apart the scans were, as well as the overall height of the head. Sixteen scans were used to create evenly spaced profiles. Each scan was imported into the CAD program, Rhinoceros 4.0, and traced using spline curves. These profiles were taken from the bottom of the head to the top; only half of the head was modeled. This was done because the head is assumed to be symmetric, and the ant head was not perfectly level when the images were captured so the scans were not symmetric. In addition, the profiles were created so that when they were mirrored over the symmetry plane, the mirrored curve would lay tangent to the original curve. This is very important for obtaining accurate results when carrying out and FEA. An illustration of this process can be seen in Figure 4 below.

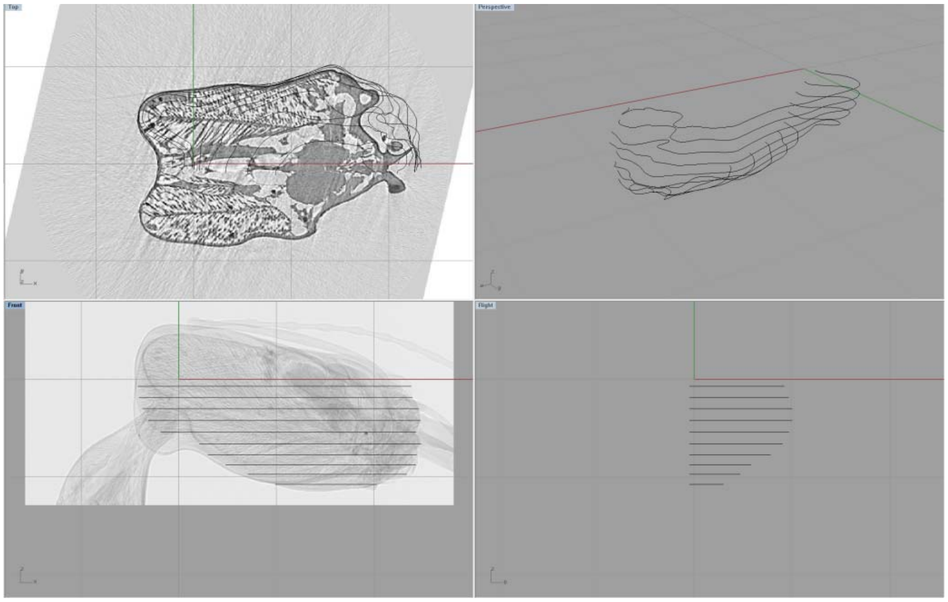

Figure 4: CAD profile sketches based on micro CT scans

Once the once CT scans were traced, a loft was created through the profiles. Because of the complex geometry, the loft would only create a feasible surface when the surface was loosely fitted to the profiles. A tighter fit resulted in major discontinuities and very twisted surfaces. Rhino 4.0's symmetry function was used to create a fully enclosed head surface. When this was done, holes remained at the top and the bottom of the head because the loft did not start and end at the symmetry plane, but rather at the first and last profiles. A patch was created on either side to enclose the surface. This however proved to be very difficult to implement. Creating a patch that would both lay tangent to the adjoining surfaces as well as connect to them required several surface trims and "match surface" commands. The full model can be seen in Figure 5 below. While it appeared to have worked within Rhino 4.0, when importing the file into other programs such as SolidWorks and ANSYS, the surfaces did not render correctly. The surface itself was extremely complex for the capabilities of the ANYSIS version available for use. It was at this point that we decided to create a more simplified model with the same general contours as the *Odontomachus* head for the FEA.

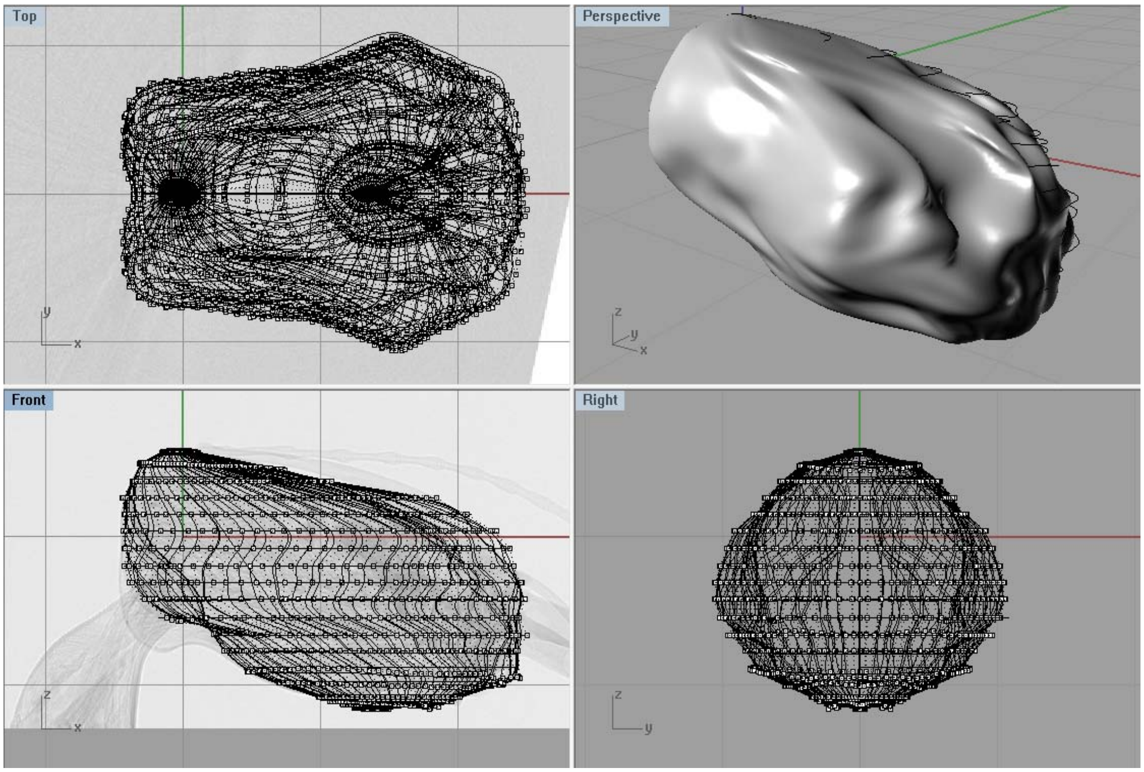

Figure 5: Completed complex *Odontomachus* head model based on CT scans

Based on this process, we gained a much better understanding of the overall shape of the head as well as how the muscles are attached to the inside surface of the head. It was noted that the head was not only elongated, which entomologists attribute to allowing for the use of longer muscles, but also tapered towards the back end. We initially thought that the head may have evolved in this way to allow the structure to act as a spring and deflect when the jaws were loaded, thus storing some of the potential energy involved in the mechanism.

2.3 Simplified *Odontomachus* Model

The simplified *Odontomachus* model was created by lofting vertical cross sections. We created the model from the two images shown in Figure 6 below and the final model can be seen below in Figure 7.

Figure 6: Front and right view of *Odontomachus bauri* specimen [16]

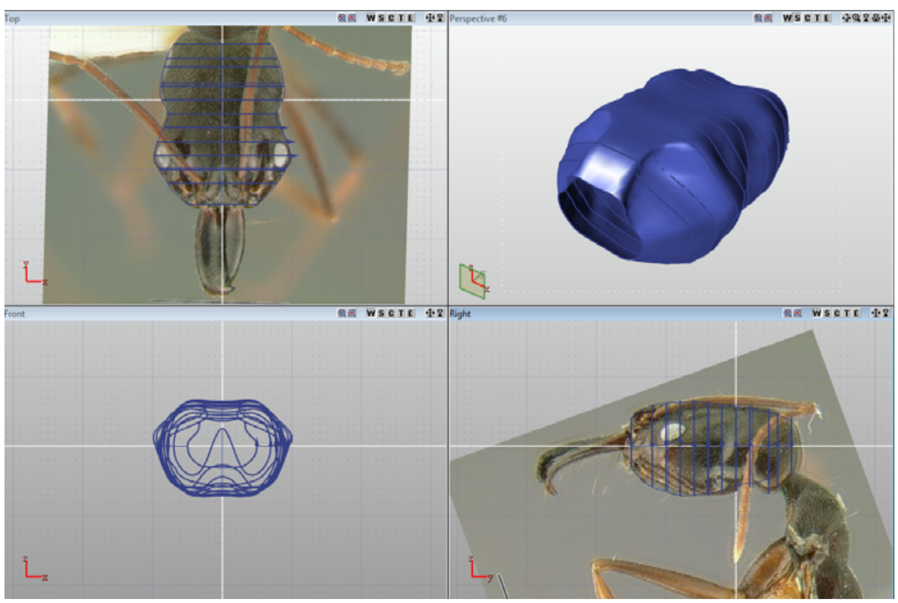

Figure 7: Simplified *Odontomachus* head model

Again, there were difficulties with enclosing the surface. It was determined that the front of the ant head would not be critical in the FEA, so it was left open while the back of the head was patched.

In order to test our idea that the head structure was actually acting as a means for storing potential energy, the original plan was to compare the *Odontomachus* model with the FEA results of a similar analysis on an *Atta* head model. *Atta*, better known as leaf cutter ants, have jaws that are optimized for generating large forces rather than high velocities. There are very distinctive difference between the *Odontomachus* and the *Atta* head shapes, as can be seen below in Figure 8. *Atta* has a shorter and wider head with a more pronounced indentation at the back center of the head. *Odontomachus* on the other hand has a more irregular shape with a thinner elongated head and a tapered back end of the head. In addition, *Odontomachus* tapers inwards about midway between the front and the back of the head while *Atta* essentially has a constant increase in width when going from the front to the back of the head.

Figure 8: *Odontomachus* (left) and *Atta* (right) specimens [16]

A simplified model of an *Atta* head to correspond to the simplified *Odontomachus* head was created as seen below in Figure 9.

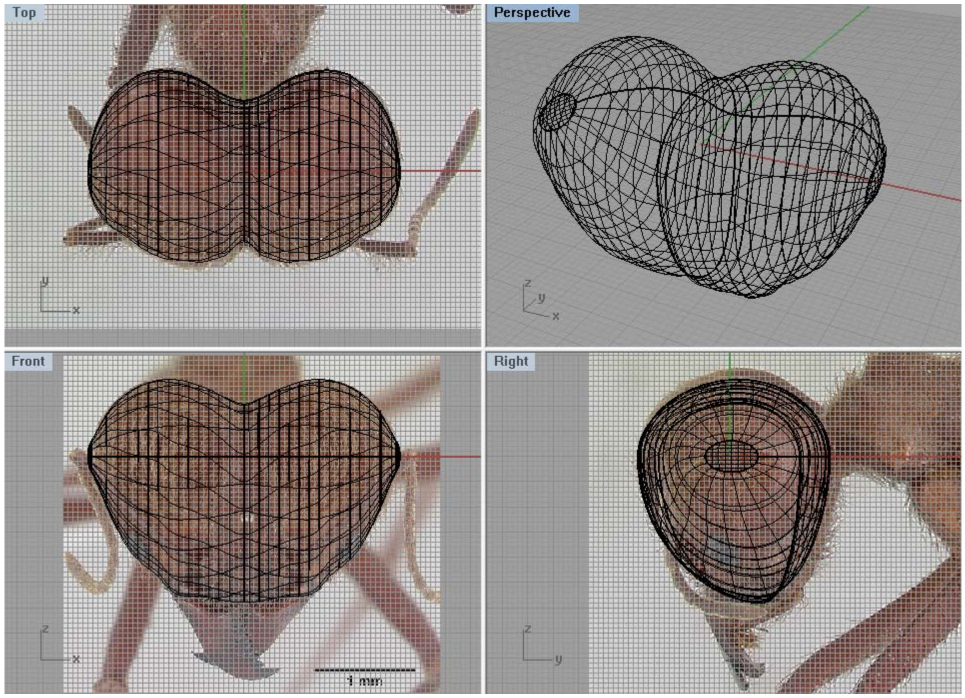

Figure 9: Simplified *Atta* head model

The final renderings of the models are shown below in Figure 10.

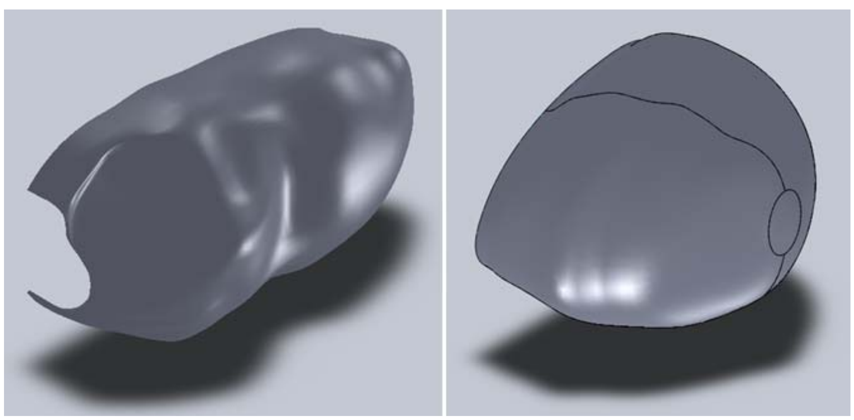
Figure 10: Final *Odontomachus* and *Atta* model renderings

The next step was to begin the finite element analyses on each of the models. As we began to work on this, however, we found that we were missing key information to carry out the analysis. As far as properties of the model itself go, we were unsure about the thickness of the cuticle, which is very important in obtaining reliable results. We were also unsure of the properties of cuticle such as the Young's Modulus of Elasticity and the Poisson Ratio. In addition, we were unsure of how the muscles attached to the inside of the head as well as where they attached. This information is essential when it comes to accurately applying forces to the model.

As we worked to answer these questions, we realized that it would be much easier to communicate with the entomologists we were working with if we had a physical model of the heads. With these models, we could physically point to what we were talking about and have them show exactly where items such as muscles were located. These models could also allow us to get a better feel for the shape of the structure. It was therefore decided that prototype models of each head would be made using the Fused Deposition Modeling machine in the Mechanical Engineering Department. These models are shown below in Figure 11. Each model was three inches from front to back which did not turn out to be a good choice for a characteristic dimension just based on observation. The *Atta* model was much larger than the *Odontomachus* model; therefore it was decided that a different characteristic dimension would be chosen for the actual FEA in order to allow us to generate comparable results.

Figure 11: *Odontomachus* (left) and *Atta* (right) rapid prototype models

After further discussion, we decided to further simplify the FEA for the initial analysis. We thought it may be more beneficial to look at several iterations of head shapes and keep the cross section of the at the symmetry plane constant while varying the profile. The models each represented half of a head, as illustrated in Figure 12 below.

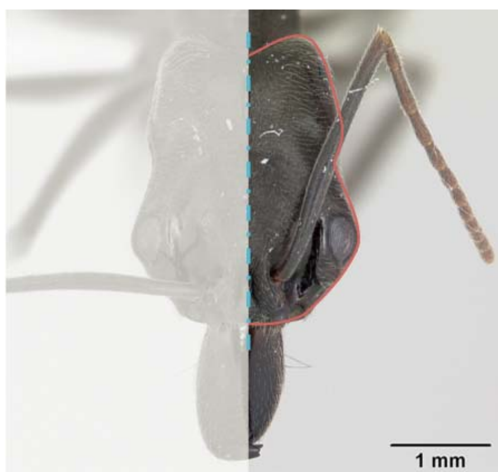

Figure 12: Model representation

These iterations included one with a simple egg shape, one with an *Atta*-shaped head profile with a flat back, and two models based on the *Atta* and *Odontomachus* profiles.

The different iterations can be seen in Figure 13. Each was modeled as a surface, and these were used in the FEAs described in the following chapter.

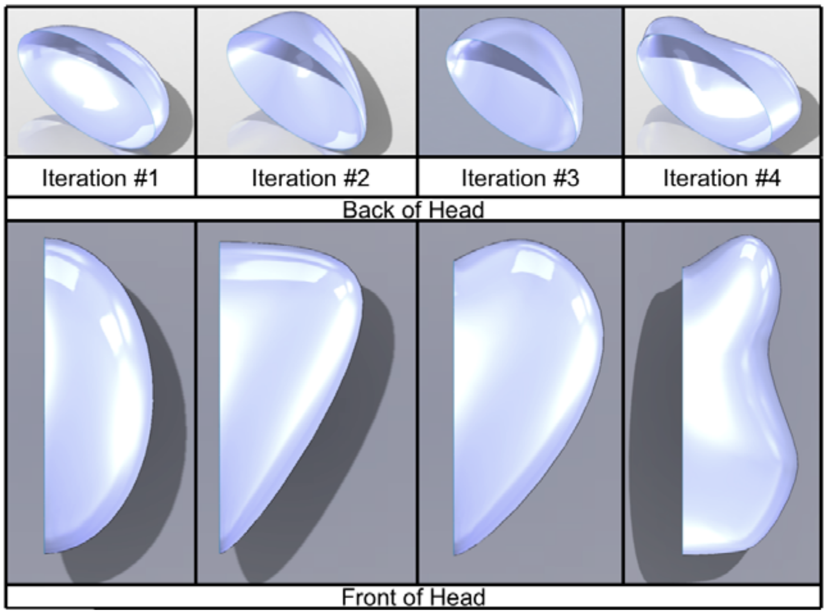

Figure 13: FEA iterations

CHAPTER 3: FINITE ELEMENT ANALYSIS

3.1 Introduction

The following chapter describes the finite element analysis portion of this project. It includes details on how the jaw closing force was calculated, an explanation of how the FEA was carried out including boundary conditions and force applications, and discusses the meaning of the results of the analysis.

3.2 Calculation of Jaw Closing Force

An estimate of the amount of force imparted on the cuticle by the muscle was required as part of the FEA. We were able to calculate this based on the maximum angular acceleration and geometry of the mandibles, their axis of rotation, the connection point between the mandibles and the apodeme, and the average mass of a mandible. The mandible itself was modeled as a cylinder 1.53 mm long with a mass of $1.45*10^{-7}$ kg. The distance from the end of the mandible to the axis of rotation was 1.38 mm, while the distance from the axis of rotation to the apodeme connection was 0.15 mm. These dimensions were based on Figure 14 below.

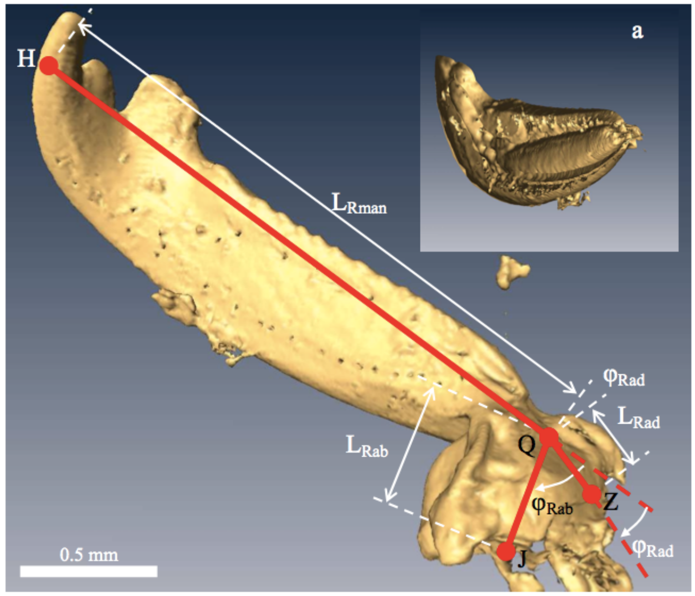

Figure 14: Detailed mandible image [13]

Figure 15 below illustrates the simplified model used in this dynamic analysis.

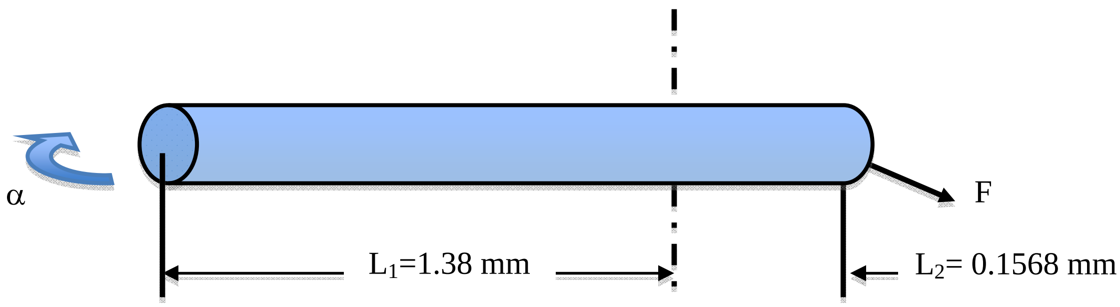

Figure 15: Simplified model for dynamic analysis

From the model, we calculated the moment of inertia as that of a cylinder at the end where the force was applied as shown in the following equations.

$$I_a = \frac{1}{3} ML^2$$

$$I_a = \frac{1}{3}\left(1.45*10^{-7} kg\right)\left(1.5368*10^{-3} m\right)^2$$

$$I_a = 1.14154*10^{-13} kg \cdot m^2$$

Using this moment of inertia along with the Parallel Axis Theorem, the moment of inertia at the axis of rotation was calculated:

$$I_b = I_a - L_2^{\ 2} M$$
$$I_b = 1.14154 * 10^{-13} kg \cdot m^2 - \left(1.568 * 10^{-4}\right)^2 \left(1.45 * 10^{-7} kg\right)$$
$$I_b = 1.1772 * 10^{-13} kg \cdot m^2$$

Based on previous research conducted by at the University of Illinois, Urbana-Champaign, the maximum angular acceleration of an *Odontomachus bauri* mandible is $8*10^8$ rad/sec^2 [4] We could then calculate the force applied at the apodeme attachment point as shown below.

$$T = I\alpha$$
$$FL_2 = I_b \alpha_{\max}$$
$$F = \frac{I_b \alpha_{\max}}{L_2}$$
$$F = \frac{\left(1.1772 * 10^{-13} kg \cdot m^2\right)\left(8 * 10^8 rad / \sec^2\right)}{1.568 * 10^{-4} m}$$
$$F = 0.6006 N$$

This force is similar to values found by researchers at the University of Illinois, Urbana-Champaign for similar *Odontomachus* species [12]. They found that, depending on the species, the adductor muscles generated between about 0.40 and 1.20 N of force.

3.3 Initial Finite Element Analysis

Two sets of FEAs were run for this project. We started with a very simplified application of loads on half of the head. Two split lines were created in the models using reference planes. The first split the model horizontally though the middle of the model, and the second split the model vertically, 0.45 mm from the symmetry plane. This location is roughly where the apodeme is located, as estimated from Figure 16 below.

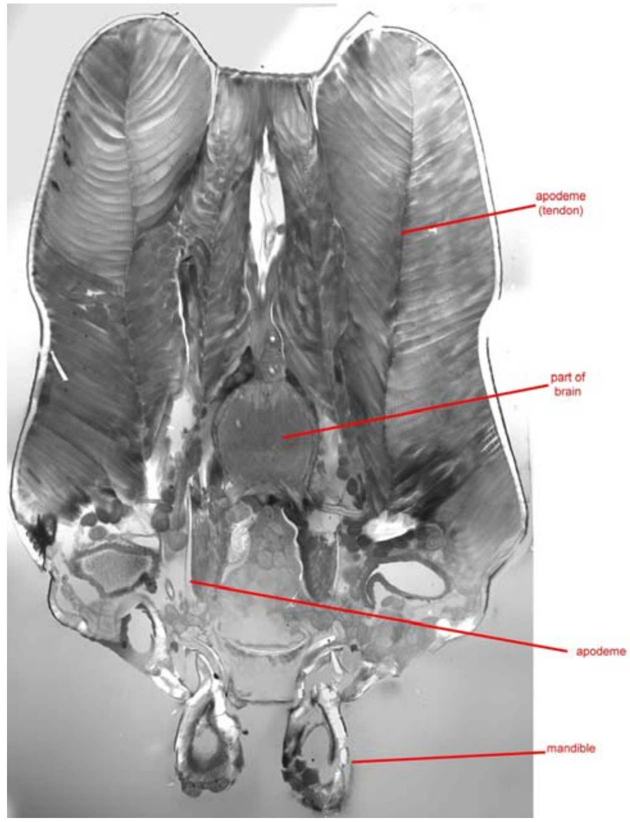

Figure 16: Detailed cross section of *Odontomachus* head

An additional plane was created 1.0 mm from the center vertical plane of the model so that part of a face could be fixed. The split lines can be seen in Figure 15 below.

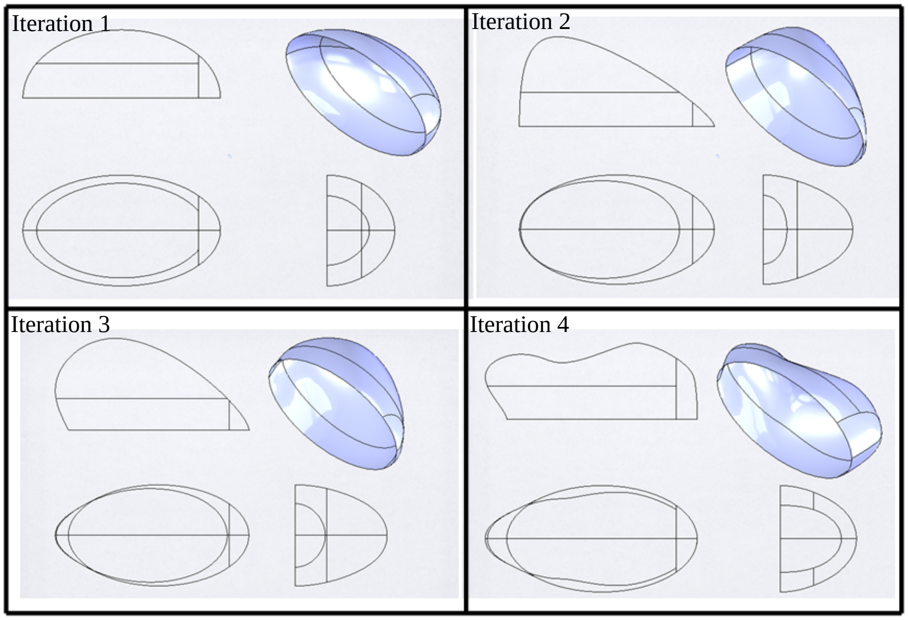

Figure 17: Split lines for the initial FEA on all iterations

The models were imported into ANSYS Workbench from SolidWorks. Points were created 0.15 mm apart from the back to the middle of the head along the split lines. The thickness of the shell was set at 0.022 mm based on measurements taken from Figure 16 above. The cuticle properties were set to a Young's Modulus of 10,000 MPa and a Poisson's Ratio of 0.3. These values were based on previous research [17].

The yz-plane was set as the symmetry plane, and loads were applied to points on the split lines. The front surfaces were set as fixed supports because that is where the mandibles would be attached. A distributed load was applied; the magnitude of the z-direction components was calculated by dividing the total force exerted by the muscles by the number of point loads used in the model. The muscles are attached at a roughly 45 degree angle. In order to create the 45 degree vector that represents the load from the muscles, a corresponding x- (for the horizontal split line) and y-force components (for the vertical split line) were added. An example of this load application for the first iteration can be seen in Figure 15 below.

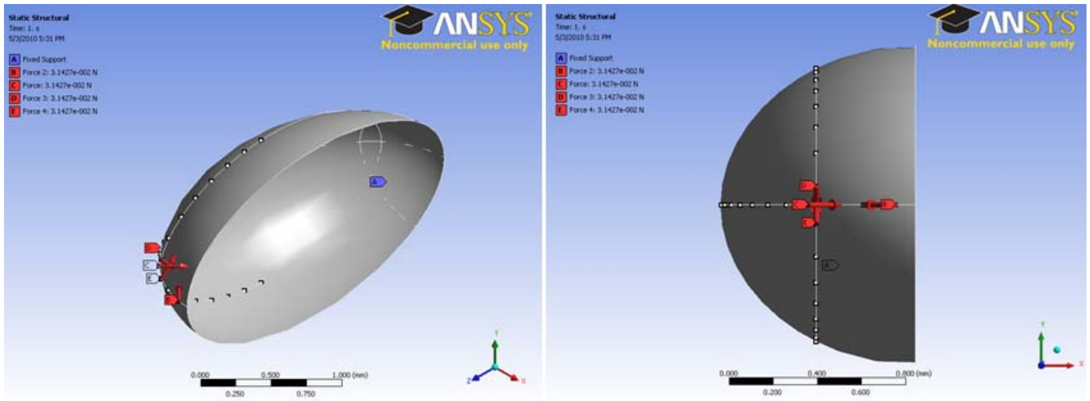

Figure 18: FEA load application for initial analysis

The results of this analysis can be seen below in Figure 19 and Figure 20. Figure 19 shows the results for the Von Mises stresses in each of the iterations, while Figure 20 shows the results for the deflections.

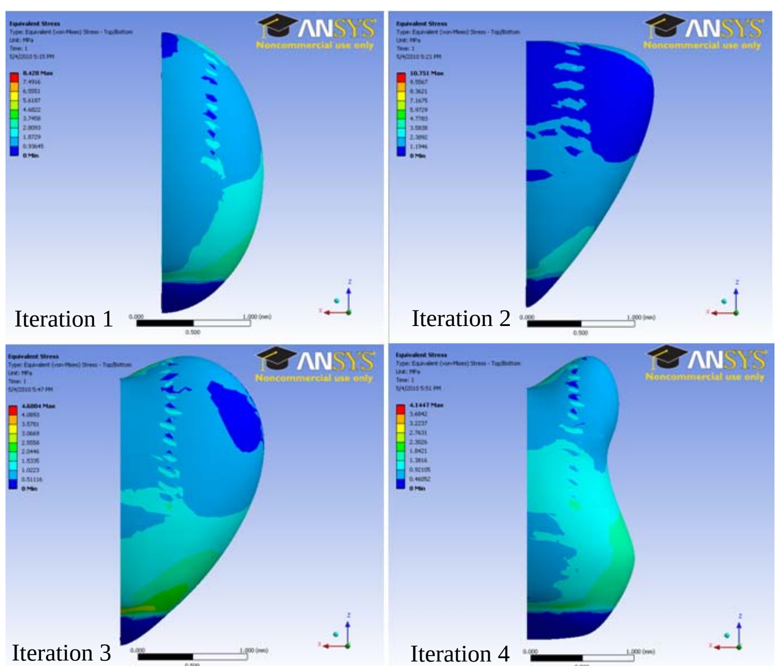

Figure 19: FEA Von Mises stress results for initial analysis

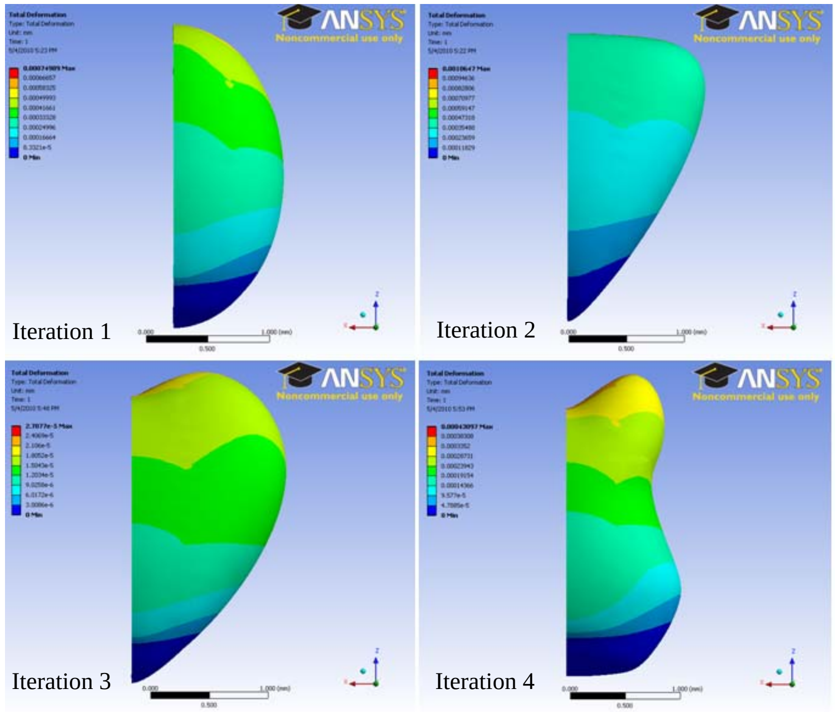

Figure 20: FEA total displacement results for initial analysis

A table of the maximum deflections and stresses is in Table 1.

Table 1: Maximum deformation and Von Mises stress for initial FEA

Iteration	1	2	3	4
Max Deformation (mm)	0.00075	0.001065	0.000027077	0.000431
Max Von Mises Stress (MPa)	8.428	10.751	4.6004	4.1447

Iteration 2 appears to have a significantly higher maximum deformation than the other four iterations, while iteration 4 which is closest to the *Odontomahcus* head shape has a much lower maximum Von Mises stress than the others. Based on this preliminary analysis, it appeared that the *Odontomachus* head shape evolved not to store potential energy and act as a spring as we thought, but rather to minimize stress.

Based on the stress plots, it was clear that stress concentrations existed at the points where load was applied. Therefore, we decided that the model may have been too simplified to accurately estimate the deflections and stresses in the systems. We decided that it was necessary to run a second analysis which had more load application locations and thus more accurately approximated a distributed load.

3.4 Refined Finite Element Analysis

The refined FEA added several split lines, which were created at 30 degree intervals. These allowed a more even distribution of load on the back of the head. An additional split line was added midway between the front and back of the head, and only a quarter of the head was modeled rather than half. The modified models can be seen below in Figure 21 below.

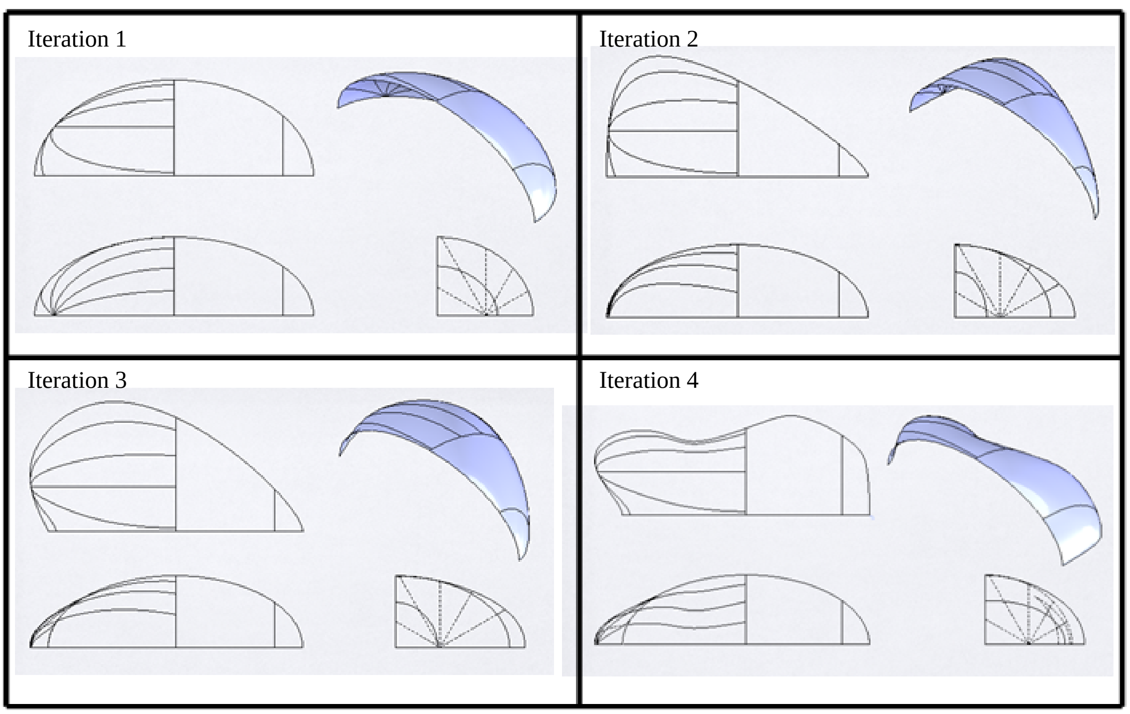

Figure 21: Split lines for the initial FEA on all iterations for refined analysis

Again, load points were created along the split lines on the back half of the head; these were spaced 0.15 mm apart. The shell was given a thickness of 0.022 mm, and the cuticle material properties were the same as those used in the previous analysis. Symmetry was set across both the yz-plane and the xz-plane. A distributed load was applied in the same manner as described in the first FEA. At the point loads located on the xz-symmetry plane, only half of the calculated loads were applied because they were located on the symmetry plane and would be doubled when the simulation was run. An example of the applied loads is below in Figure 22.

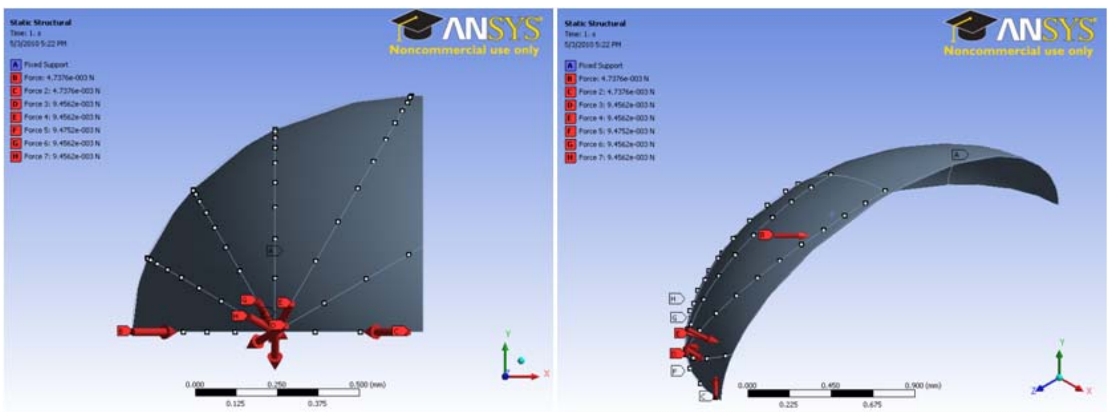

Figure 22: FEA load application for refined analysis

The results of this analysis can be seen in Figure 23 and Figure 24 below. It is clear that this model is a much better simulation of a distributed load on the models because there are not distinctive stress concentrations at the load locations.

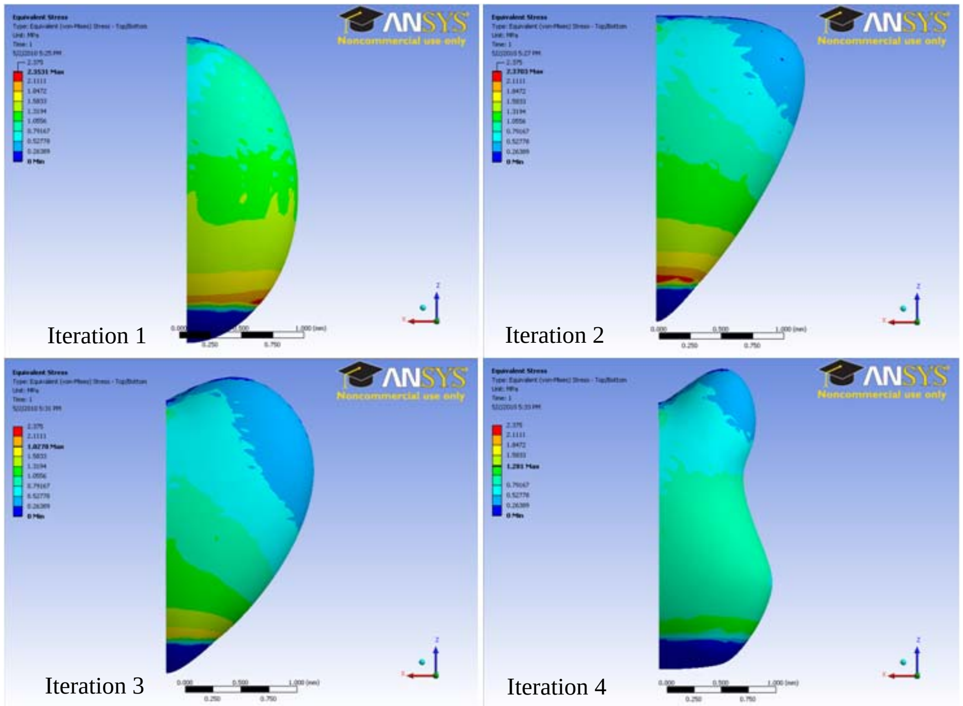

Figure 23: FEA Von Mises stress results for refined analysis

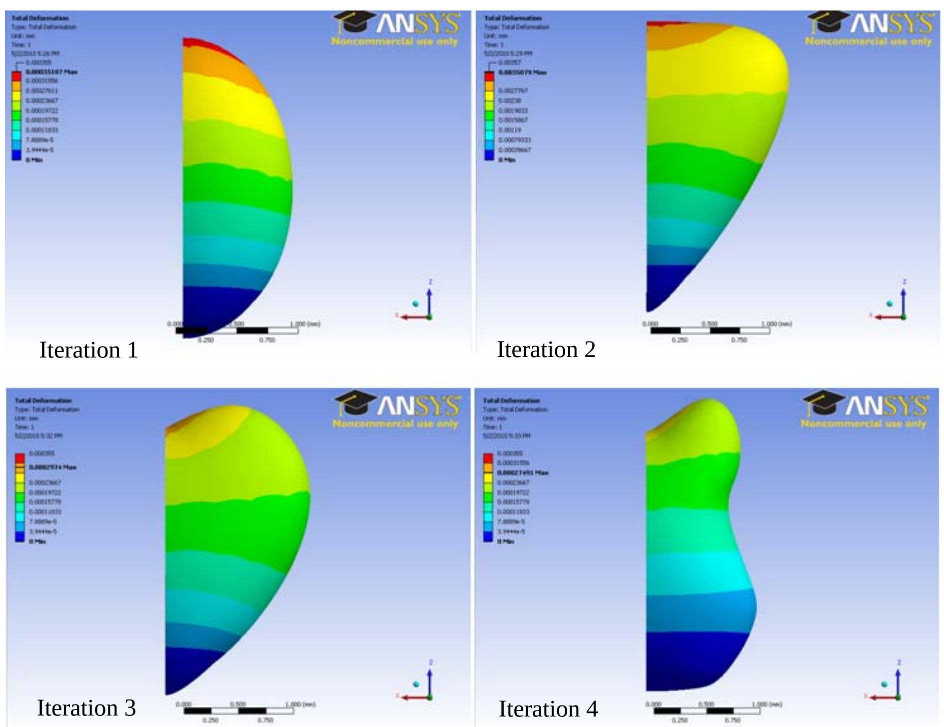

Figure 24: FEA total displacement results for refined analysis

Each set of plots has been formatted so that the same color scale is used, with the exception of iteration 2 for the deflection. This is because the maximum deflection of this model is almost ten times greater than the other iterations. A table of the maximum deformation and Von Mises stress can be seen below.

Table 2: Maximum deformation and Von Mises stress for refined FEA

Iteration	1	2	3	4
Max Deformation (mm)	0.000351	0.00287	0.000297	0.000275
Max Von Mises Stress (MPa)	2.3531	2.3703	1.878	1.281

These results show the same trends as the previous analysis. Based on the results, it appears that the *Odontomachus* head has evolved to reduce both stress and deflection. The results contradict our initial hypothesis that the *Odontomachus* head had evolved to act as a means of potential energy storage. If this were the case, deflections similar to iteration 2 would be seen. Instead, iteration 4 (the one closest to the actual *Odontomachus* head shape) shows both the smallest amount of deflection as well as the lowest maximum Von Mises stress of any of the models tested.

CHAPTER 4: CONCLUSION

The goal of this project was to reverse engineer the *Odontomachus* trap-jaw mechanism. We were interested in this system because it is the fastest mechanical movement known in nature. The ants are able to close their jaws at up to 145 mph.

The first step in this project was creating a kinematically correct model to allow us to understand the scale of the ant and the degrees of freedom of the body structure. A detailed computer model of the head was then created, allowing us to study the complex geometries of the head's external surface. Once that was complete, a simplified model of the head was created, along with a model of the *Atta* ant head. The *Atta* model was created to allow for comparison between a structure optimized for high velocity generation with one optimized for high force generation. FDM prototypes of these computer models were then created to facilitate communication between us and entomologists.

It was then determined that it would be more beneficial to further simplify the models and create several head shape iterations to test our hypothesis that the *Odontomachus* head had evolved to allow it to deflect and store potential energy when the mandibles were loaded. Four head shapes were tested, including one with the same profile as *Atta*'s head and another with the same profile as *Odontomachus*. The results did not agree with our hypothesis; the *Odontomachus* structure actually had the least amount of deflection. At the same time, it also had the smallest maximum stress. Therefore, we conclude that the head shape has evolved to reduce stress in the cuticle.

This project is part of a longer term Master's thesis which will conclude at the end of next year. In the coming year, we would like to continue with the structural analysis of the head cuticle. This will be done by carrying out a more complex analysis with a more detailed model of the head using the finite element program Abacus, which is capable of performing a more detailed analysis than the CAE software used in this project (ANSYS). We plan in integrating the tentorium, an internal support structure, into the analysis to determine how it affects the structural integrity of the cuticle. Time permitting, we would also like to look at the interface between the head and the neck, and explore how the joint can withstand the high loads it experiences. It would also be very beneficial to investigate the locking mechanism of the jaws more closely and determine how it works, as well as look at how the jaws decelerate before impacting one another. The ultimate goal is to create a working physical model of the trap-jaw mechanism based on the *Odontomachus* design.

WORKS CITED

[1] Benyus, Janine M. Biomimicry Innovation Inspired by Nature. New York: Harper Perennial, 2002.

[2] Holldobler, B., and E. O. Wilson. The Ants. Cambridge, MA: Harvard UP, 1990.

[3] Gronenberg, Wulfila. "The trap-jaw mechanism in the dacetine ants *Daceton armigerum* and *Strumigenys* sp." Journal of Experimental Biology 199 (1996): 2021-033.

[4] Patek, S. N., J. E. Baio, B. L. Fisher, and A. V. Suarez. "Multifunctionality and mechanical origins: Ballistic jaw propulsion in trap-jaw ants." PNAS 103 (2006): 12787-2792.

[5] Paul, Jurgen, and Wulfila Gronenberg. "Optimizing force and velocity: Mandible muscle fibre attachments in ants." Journal of Experimental Biology 202 (1999): 797-808.

[6] Paul, Jurgen. "Review: Mandible movements in ants." Comparative Biochemisty and Physiology A (2001): 7-20.

[7] Gronenberg, W. "The fast mandible strike in the trap-jaw ant *Odontomachus* I. Temporal properties and morphological characteristics." Journal of Comparative Physiology A 176 (1995): 391-98.

[8] Gronenberg, W., and J. Tautz. "The sensory basis for the trap-jaw mechanism in the ant *Odontomachus bauri*." Journal of Comparative Physiology A 174 (1994): 49-60.

[9] Gronenberg, W. "The fast mandible strike in the trap-jaw ant *Odontomachus* II. Motor control." Journal of Comparative Physiology A 176 (1995): 399-408.

[10] Just, Stefan, and Wulfila Gronenberg. "The control of mandible movements in the ant *Odontomachus*." Journal of Insect Physiology 45 (1999): 231-40.

[11] Spagna, Joseph C., Antonis I. Vakis, Chris A. Schmidt, Sheila N. Patek, Xudong Zhang, Neil D. Tsutsui, and Andrew V. Suarez. "Phylogeny, scaling, and the generation of extreme forces in trap-jaw ants." Journal of Experimental Biology 211 (2008): 2358-368.

[12] Vakis, Antonis. "Two-dimensional biomechanical analysis of the extremely fast strikes of trap-jaw ant mandibles." Thesis. University of Illinois at Urbana-Champaign, 2005.

[13] Vakis, Antonis, and Seung min M. Yeo. Biomimetic design: the case of trap-jaw ant mandibles. University of Illinois at Urbana-Chamgaign. 29 Jan. 2009 <https://netfiles.uiuc.edu/avakis2/www/trapjaws.pdf>.

[14] Gronenberg, Wulfila. "The trap-jaw mechanism in the dacetine ants *Daceton armigerum* and *Strumigenys* sp." Journal of Experimental Biology 199 (1996): 2021-033.

[15] Barbakadze, N., S. Enders, S. Gorb, and E. Arzt. "Local mechanical properties of the head articulation cuticle in the beetle *Pachnoda marginata* (Coleoptera, Scarabaeidea)." Journal of Experimental Biology 209 (2006): 722-30.

[16] AntWeb. The California Academy of Sciences. Web. 04 May 2010. <http://antweb.org>.

[17] Vincent, Julian F.V., and Ulrike G.K. Wegst. "Design and Mechanical Properties of Insect Cuticle." Arthropod Structure & Development 33 (2004): 187-99. Web.